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Manuscript title: Use of fall cones to determine Atterberg limits: a review

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Contribution by G. E. Barnes

The authors have presented an interesting review of the use of fall cones to determine Atterberg limits. Wood (1983) recognised that the fall cone test was not suited to determine the true plastic limit: "It is not clear how the cone penetrometer plastic limit gives an indication of the water content at which soil changes from the brittle to the plastic state". The discusser wishes to comment on the strength-water content relationship and the plastic strength limit, *PSL* (*PSL* is preferable to *PL* to reinforce that it is a strength-based value with no relation to the true plastic limit.) which is based on

$$s_{\mathrm{uFC(PSL)}} = R_{\mathrm{MW}} \text{ x } s_{\mathrm{uFC(LL)}} \qquad (15)$$

Wood and Wroth (1978) stated that "Studies…have shown that it is reasonable to assume that soil can be assigned a unique strength at the liquid limit" and suggested a strength of 1.7 kPa was satisfactory. Wood (1983) stated "…it seems that if round numbers are shown for convenience then R [R_{MW}] = 100 and C_{LL} [$s_{\mathrm{u(LL)}}$] = 1.7 kN/m^2 is not too bad for a first shot". This produces $s_{\mathrm{u(PSL)}}$ = 170 kPa. The shear strength at the liquid limit is not unique, Table 1. It is doubtful that the fall cone factor K in Hansbo's expression (equation 1) is constant throughout the range of water contents between the liquid and plastic limits. K for the 80 g 30$^{\mathrm{o}}$ cone would be 0.867 for $s_{\mathrm{u(LL)}}$ = 1.7 kPa. Adopting the cone factor of 0.8 from BS EN ISO 17892-6:2017 $s_{\mathrm{u(LL)}}$ would be 1.57 kPa. Koumoto and Houlsby (2001) showed that, theoretically, K could vary from about 1 for a rough cone to 2.0 for a smooth cone and, experimentally, between 0.85 and 1.2. Brown and Huxley (1996) and Brown and Downing (2001) found that although Hansbo's expression with $K \approx 0.8$ applies to water contents near the liquid limit, at lower liquidity indices much lower cone factors were appropriate.

Based on Schofield and Wroth (1968) and Wroth and Wood (1978) the strength gain factor R_{MW} has been assumed as 100 by many researchers but the authors' Figs. 3 and 4 show this assumption to be false. A wide variation of R_{MW} has been found by several authors (Karlsson, 1961; Whyte, 1982; Wood, 1983; Wijeyakulasuriya 1990; Brown and Downing, 2001; Nagaraj et al, 2012; Vardanega and Haigh, 2014).

There appears to be a mineralogical effect on R_{MW}. Dumbleton and West (1970) reported different suctions and vane shear strengths at the plastic limit and liquid limit for kaolinite and montmorillonite, also giving different R_{MW} values, 25 and 110, respectively. Soils with a high proportion of kaolinite would not comply with the Wroth and Wood (1978) relationship (R_{MW} = 100). Prakash and Sridharan (2006) recognised significant differences in cone penetration behaviour between soils of low plasticity, being dominated by kaolinite, and those of high plasticity, containing montmorillonite. The strengths at the plastic limit have been shown to be much lower for soils that plot below the A-line on Casagrande's plasticity chart compared to above (Barnes, 2013a).

From a large database of fall cone tests on 101 soils Vardanega and Haigh (2014) reported a semi-logarithmic model between undrained shear strength, s_u and water content, w

$$\ln(s_u) = S - H.w \qquad (16)$$

Given the liquid and plastic limits for each soil these can be plotted as s_u vs. I_L, Fig. 11. With 101 soils there are 101 relationships. A range of $s_{uFC(LL)}$ (1.55 – 2.35 kPa) is obtained from the S and H values and a wide range of R_{MW} was obtained (7 – 152, mean = 33). The PSL and I_L for each soil can be determined from equations 17 – 20 and are plotted on Fig. 11.

$$PSL_{25} = \frac{S - \ln(s_{uLL} \times 25)}{H} \qquad 17$$

$$PSL_{100} = \frac{S - \ln(s_{uLL} \times 100)}{H} \qquad 18$$

$$I_{L25} = \frac{PSL_{25} - PL}{LL - PL} \qquad 19$$

$$I_{L100} = \frac{PSL_{100} - PL}{LL - PL} \qquad 20$$

The authors' fall cone consistency index (equation 12) equals 1 for each value of PSL_{25} and equation 14 then gives the s_u - I_L relationship for each soil, Fig. 11. As the authors point out PSL_{100} mostly lies in the brittle region, well below the plastic limit. Even PSL_{25} can give a wide range of consistencies from brittle to plastic, sticky to non-sticky. Nevertheless, below the plastic limit the s_u - I_L relationship follows a significantly different path (Marinho and Oliveira, 2012; Vinod et al, 2013).

Interpolation for strengths between the PSL and the liquid limit depends on the assumption of linearity of the semi-logarithmic relationship. However, these relationships are distinctly curved, as shown in the original data in Skempton and Northey (1953), (Fig. 4), and confirmed several times since (Wood,1985; Wasti and Bezirci, 1986; Harison, 1988; Wijeyakulasuriya 1990; Stone and Phan, 1995; Feng, 2000; Koumoto and Houlsby, 2001; Muntohar and Hashimi, 2005; Barnes, 2019).

Harison (1988) demonstrated a bi-linear semi-logarithmic relationship. From analysis of several sources (Black and Lister, 1978; Dumbleton and West, 1970; Wasti and Bezirci, 1986; Northmore et al, 1992; Stone and Phan, 1995; Feng, 2000; Koumoto and Houlsby, 2001) Barnes (2019) has shown the relationship from fall cone and vane tests to be multi-linear with a typical example given in Fig. 12. With data available only near the liquid limit R_{MW} would be obtained from line A giving a significant underestimate of the *PSL*. Sources such as Sherwood and Ryley (1970) were not included because the cone penetrometer data would only provide line A.

Extrapolation from single lines through A and B or A, B and C would also underestimate the *PSL*. Vardanega and Haigh (2014) point out that equation 16 only applies to $0.2 < I_L < 1.1$ since less data was available below $I_L = 0.2$. Using the discusser's apparatus (Barnes, 2009; Barnes, 2013a; 2013b) a stiff transition in the toughness-liquidity index relationship in the region $0 < I_L < \sim 0.2$ was found (Barnes, 2019) providing an additional line close to the plastic limit, Fig. 13.

The shear strength at the liquid limit, the fall cone factor and the strength gain factor are not constants but vary significantly, the relationship between shear strength and water content is not linear but curved, or with enough data can be interpreted as multi-linear. A large published database shows that the consistency at the plastic strength limit PSL_{100} is mostly brittle and even at PSL_{25} many soils would also be brittle.

Authors' Reply

The authors thank the discusser for his interest in the review paper (O'Kelly *et al*. 2018). The authors agree with many of the statements in the discussion and in this reply give more elaboration and clarification on some of the key points raised. In his concluding statement, the discusser states "The shear strength at the liquid limit, the fall cone factor and the strength gain factor are not constants but vary significantly". We will now study each of these elements in turn.

Shear Strength at Liquid Limit

It is well documented that the undrained shear strength at the Casagrande liquid limit ($s_{\mathrm{u(LL_{cup})}}$) has a relatively wide range of typically 1–3 kPa (Nagaraj *et al*. 2012; O'Kelly, 2019). O'Kelly (2019) has recently explained that some very high deduced values of $s_{\mathrm{u(LL_{cup})}}$ are perhaps due to insufficient data in the original regressions used for their determination, the curve-fitting approach adopted and various measurement inaccuracies arising from the strength apparatus employed. The value of the Casagrande liquid limit (LL_{cup}) is also partly dependent on the hardness of base material of the percussion-cup apparatus used (Haigh, 2016, O'Kelly, 2019), such that some variation in the value of LL_{cup} and hence the associated $s_{u(LL_{cup})}$ is therefore expected for apparatuses with different base hardness.

However, for the fall-cone liquid limit (LL_{FC}), a standardised fall-cone device with given cone mass, apex angle and smooth cone surface produces values of LL_{FC} that correspond to a set (predefined) value of undrained shear strength (i.e. $s_{uFC(LL)}$). For example, the BSI 30°–80g fall cone, with LL_{FC} defined as the water content coincident with 20 mm of cone penetration, would mobilise an $s_{uFC(LL)}$ value of ~1.7 kPa, implying a cone factor (K) value of 0.867. It is true that the pertinent value of K either needs to be calculated theoretically (equation (7): cf. Koumoto and Houlsby, 2001) or calibrated by assigning the cone penetration depth value at LL_{FC}. However, LL is a somewhat arbitrary criterion as the transition from plastic to liquid state is not abrupt (unlike the change from plastic to brittle state). Hence, once a criterion for LL is established (assigned), LL_{FC} thus implies a fixed $s_{uFC(LL)}$ (or a variable K) value if one invokes Hansbo's (1957) equation (equation (1)).

Variability of the fall-cone factor

The fall-cone test can be examined based on plasticity analysis (Koumoto and Houlsby, 2001) to demonstrate a relationship between the cone mass and soil undrained shear strength (Hansbo, 1957) if the soil is assumed to be a perfectly plastic material. For soil with this simplified constitutive behaviour, the cone factor (K) should be constant. Undrained shear strength (s_u) values measured using different strength test methods for saturated remoulded physically-identical specimens of a given soil inevitably show some experimental variation. Therefore, calibration of $s_{uFC(LL)}$ against s_u data measured by other means (e.g. laboratory vane shear tests) may show some variation in the 'strength' at LL owing to the differences between the stress paths, strain rates and other parameters utilised by different test methodologies (see Haigh *et al*. (2013) and O'Kelly (2013, 2014)). The discusser's Table 1 shows this variability, although it is possibly exaggerated by the inclusion of data for undrained shear strength at the LL_{cup}, with the value of LL_{cup} often not coincident with LL_{FC} measured for a given soil. The datasets summarised in the discusser's Table 1 also include data for organic fine-grained (sediment) soils, although the Atterberg limit concepts are not appropriate for those soils containing fibrous organic material (O'Kelly, 2015, 2016). The discusser uses equation (16) (from Vardanega and Haigh, 2014) to establish an undrained shear strength range of 1.55 to 2.35 kPa at LL_{FC}. This strength variability largely arises from the individual fitting functions used, so some statistical variability is expected here, since a semi-logarithmic function was imposed on the data. This does not imply that the undrained shear strength at LL_{FC} has a range of values, but is an artefact of the assumption of linearity in the semi-logarithmic relationship which, as the discusser rightly points out, is only approximate. When establishing the regressions to the whole dataset considered, the undrained shear strength at LL_{FC} was set to 1.7 kPa following the suggestion of Wroth and Wood (1978): it is pleasing that 1.7 kPa is roughly in the middle of the range quoted by the discusser.

Statistical function to characterise strength variation in the plastic range (strength gain from LL to PL)

The discusser states that "Interpolation for strengths between the *PSL* and the liquid limit depends on the assumption of linearity of the semi-logarithmic relationship. However, these relationships are distinctly curved". (The PSL is the plastic strength limit). The authors agree with this statement. In our paper, however, we do not say that the assumption of the semi-logarithmic relationship was theoretically justified. As pointed out in Vardanega and Haigh

(2014), there is no theoretical reason to favour the semi-logarithmic fitting over another, with power-law fitting shown to be statistically more acceptable. Hence, the latter approach was adopted in formulating equations (12)–(14) presented in O'Kelly *et al*. (2018) (see also Kodikara *et al*. (1986) and Feng (2000, 2001) who showed the use of the power law fitting for undrained shear strength variation with water content in the plastic range). One may also use logarithmic liquidity index to predict fall-cone undrained shear strength (Koumoto and Houlsby, 2001). Should enough data be available to map the undrained shear strength variability over the water content range of interest, multi-linear interpolation may well be a useful tool for the understanding of soil behaviour. However, for applications in which extrapolation of data needs to be undertaken to interpolate soil undrained shear strength for a given water content, sufficient data is usually not available to accurately predict the form of the pertinent multi-linear relationship.

If one accepts the multi-linear behaviour shown in Fig. 12 as representative, then semi- or bi-logarithmic regression analysis of s_u–w data and extrapolation to the thread-rolling PL value for a given soil would deduce a value of undrained shear strength at the plastic limit that was substantially lower than its actual s_u value at the standard PL. We hypothecate the following:

(1) It would therefore follow that deduced s_u values for the standard PL from semi- or bi-logarithmic regression are (possibly grossly) conservative and consequently this may reduce the possibility of the few identified soils by the discusser being brittle at their PL_{25} water contents;

(2) The range of strength gain factor (R_{MW}) values identified considering the LL_{cup} and thread-rolling PL is conservative; the actual R_{MW} range would be greater.

The authors wish to also comment on the introduction of the toughness parameter by the discusser.

Toughness–liquidity index relationship

For water contents within the adhesive plastic region, fine grained soil exhibits zero toughness, but has a measurable undrained shear strength. The authors deliberately avoided discussion of strength for liquidity indices below 0.2, as soil plasticity behaviour is required for analysis of the fall-cone test using equation (1). Once soils potentially become brittle, the analysis using equation (1) becomes questionable at best. Whereas the fall cone approach does not measure toughness, the 'Barnes Apparatus' (Barnes, 2009, 2013a, 2013b) allows for an analysis of soil toughness, thus providing for a different method of analysis of soil behaviour for water contents below the brittle transition point. The data shown in Fig. 13 do indeed show a rapid increase in soil toughness for reducing water content close to PL. Whether this is better interpreted as a bi-linear relationship, as shown in Fig. 13, or as a non-linear function such as a power-law is worthy of further study.

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Table 1

$s_{u(LL)}$ kPa	Source
2.65	Casagrande, 1939
0.7 – 1.75	Skempton and Northey, 1953 (in Wroth and Wood, 1978)
1.3 – 2.4	Youssef et al, 1965
0.5 – 5.6	Wasti and Bezirci, 1985
1.5	Atkinson, 1993
1.2 – 12, average 4.9	Kayabali and Tufenkci, 2010
0.9 – 3.9	Haigh et al, 2013
0.64 – 2.1 mineral soils	O'Kelly, 2013
0.86 – 0.98 organic sediments	O'Kelly, 2013
0.7 – 2.65	Vardanega and Haigh, 2014
1.6 – 2.4	Present investigation

Figure captions

Fig. 11 Undrained shear strength – liquidity index relationships (data from Vardanega and Haigh, 2014)

Fig. 12 Example of multi-linear relationship (From Dumbleton and West, 1970)

Fig. 13 Toughness relationship Bentonite

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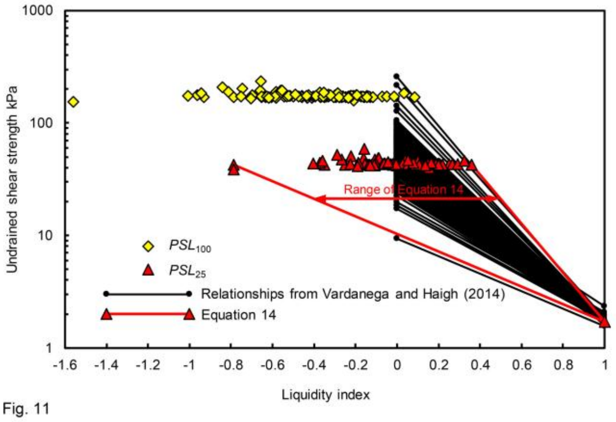

Fig. 11

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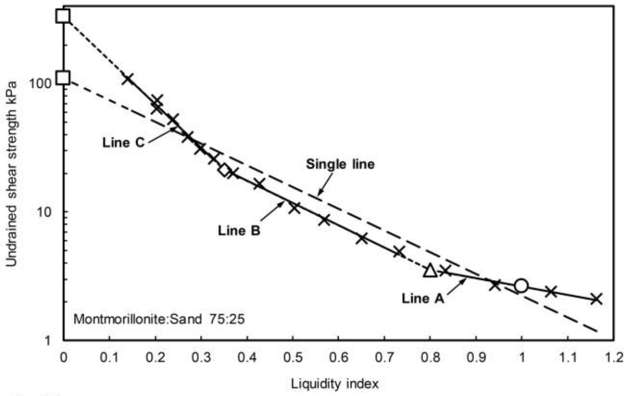

Fig. 12

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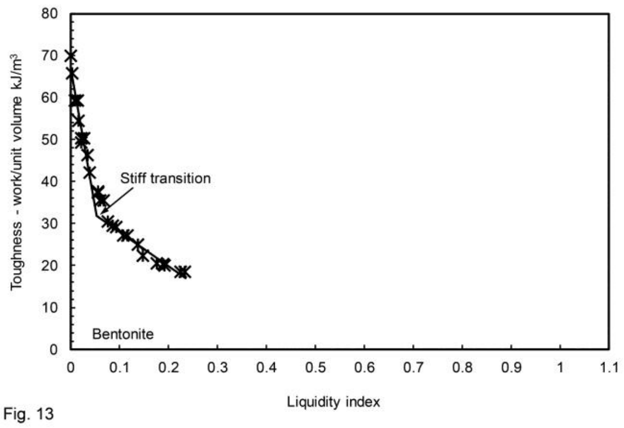

Fig. 13